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MATERIAL PROBLEMS FOR HIGH TEMPERATURE HEAT PIPES

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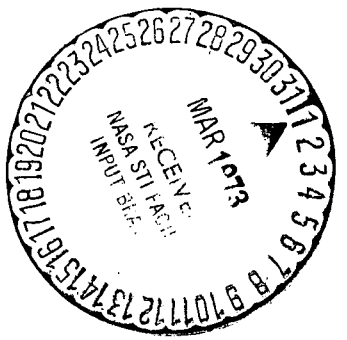

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16. Abstract

Mechanisms involved in the corrosion of the heat pipes are discussed. One mechanism connected with the solubility of the wall material in the heat carrier is responsible for mass transfer from the cooling zone into the heating zone. Another mechanism related to the accumulation of impurities in the heating zone. Another mechanism related to the accumulation of impurities in the heating zone leads to corrosion attack at the wall of that area. Approaches for avoiding heat zone corrosion are described. An operational heat pipe life of 10,000 hr in a temperature range from 1500 to 2000 deg is thought possible.

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MATERIAL PROBLEMS FOR HIGH TEMPERATURE HEAT PIPES

Claus A. Busse

1. INTRODUCTION

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The development of heat pipes for operational temperatures between about 1500° C to 2000° C was started about six years ago. These dealt with questions which have appeared in the direct conversion of heat into electricity. In particular, they dealt with the problem of heat conduction through the emitters of thermionic converters. The first experiments with high temperature heat pipes usually ended after a few hours because of the penetration of the heat pipe wall. They already showed that corrosion represents a major problem. In the following we will give a summary of the presently known corrosion mechanisms in high temperature heat pipes. We will report on results which have been achieved in solving the corrosion problem.

2. CORROSION MECHANISMS

2.1 Experimental Findings

Phenomenologically, two types of corrosion are distinguished in high temperature heat pipes: mass transport and heating zone corrosion. Both will first be explained by means of examples.

Figure 1 shows a characteristic case of mass transport. This

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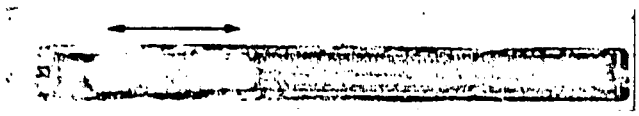

Figure 1. SGS-Ta heat pipe with Tl as a heat conductor after 2640 hours at 1600° C.
Average heating performance density 80 W/cm^2, normal longitudinal cross-section, Tl is removed.

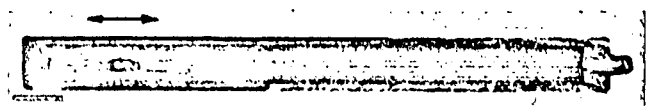

Figure 2. Nb-1 Zr heat pipe with Li as the heat carrier after 11 hours at 1500° C.
Average heat performance density 117 W/cm^2, horizontal longitudinal section, upper half, Li removed.

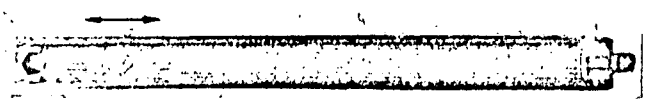

Figure 3. Ta heat pipe with Li as heat carrier after 9 hours at 1600° C.
Average heat performance density 156 W/cm^2, horizontal longitudinal section, lower half, Li removed.

Figure 1 through 3. Examples of corrosion attack in heat pipes. The arrows indicate the heating zone; operation in the horizontal position.

is a heat pipe made of SGS-Ta[1] (Ta with very little oxygen and grain stabilized by traces of Y) where Tl is the heat carrier. It is operated at 1600° C. Longitudinal grooves along the inner wall of the heat pipe represent the capillary structure. We can observe the heating zone (indicated by an arrow) where there is a thick layer. A closer investigation of the heat pipes showed that the covering came from both cooling zones, especially

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[1] SGS means stabilized grain size.

from the ends of the heat pipe. Due to this mass transport, in general there is an overheating of the heating zone, because the layer prevents the vaporization of the heat carrier. Sometimes the removal of wall material in the cooling zone leads to a leak.

Figures 2 and 3 give examples of the heat zone corrosion. These are Li heat pipes with Nb-1Zr and Ta as the wall material. These are operated at 1500° C and 1600° C, respectively. In both cases the wall was perforated in the heating zone after a few hours. In contrast to mass transport corrosion, there is practically no corrosion attack in the cooling zones when heating zone corrosion occurs.

2.2 Mass Transport

It is relatively easy to interpret the corrosion findings in the case of mass transport. When the condensate flows back from the cooling zone to the heating zone, wall material in the heat carrier goes into solution. The dissolved material together with the heat carrier reaches the vaporizing surface in the heating zone. There it is enriched and precipitates as soon as the saturation concentration is exceeded. Figure 4 shows a cross-section through the vaporizing surface for a W heat pipe operated /39 with Pb in which longitudinal grooves in the inner wall of the pipe serve as the capillary structure. It can be seen that W dendrites from the edges of the grooves have built up on the surface of the Pb, and the groove opening is gradually closed.

It is easy to specify a quantitative relationship for the mass transport [1]. If $\dot{q}$ is the heat performance density of the heat pipe, t the operational time and L the heat of vaporization, the total amount of heat carrier which is vaporized per unit of area is $\dot{q}t/L$. Let us call $\bar{x}$ the average mass fraction of wall

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Figure 4. Cross-section through the miniscus of a capillary groove filled with Pb (right picture half) in the heating zone of a W heat pipe with Pb as the heat carrier after 1000 hours at 1600°C.

Operation in the horizontal position with an average heating density of 80 W/cm^2

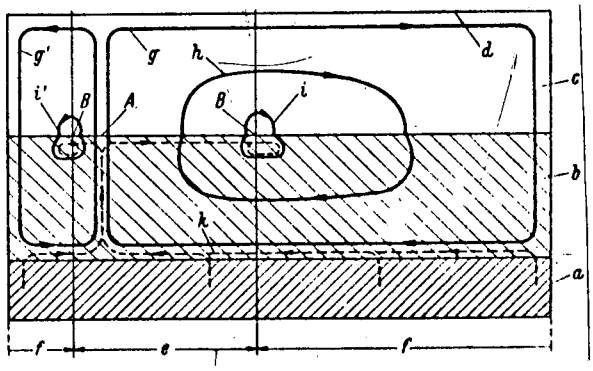

Figure 5. Circulation diagram of the heat pipe shown in Figures 2 and 3.

a-Wall, b-liquid, c-vapor volume, d-axis of the heat pipe, e-heating zone, f-cooling zones, g, g' h, i and i' are Li streamlines described in the text, k-path of the oxygen (shown with dashed lines), A-point mentioned in the text, B-end of the heating zone.

material which is dissolved in the heat carrier which arrives in the heating zone. Then $\bar{x}\dot{q}t/L$ is the total amount of separated wall material per unit area in the heating zone. If it is assumed that this precipitated material is a uniform layer having an average density ϱ, then the thickness s of the layer becomes

$$s = \bar{x}\dot{q}t/\varrho L \tag{1}$$

The layer thickness depends on the heat power density $\dot{q}$ and is proportional to it. Corrosion experiments should therefore not be carried with heat performance densities which are too low.

2.3 Hot Zone Corrosion

Hot zone corrosion probably is based on impurities. In the case of the heat pipes shown in Figures 2 and 3, we were able to show that oxygen in the wall material is the most important impurity[2]. The corrosion process is based on the interaction of thermodynamic and hydrodynamic effects and consists of the following three steps.

The basis for the corrosion process is the two-phase circulation of the Li. Figure 5 shows (very distorted) a longitudinal cross-section through the heat pipe. The wall is designated by a, and there is a liquid channel b, a vapor space c up to the axis d of the heat pipe. Also there are the cooling zones F which enclose the heating zone e on both sides. The Li circulates along two circuits which are indicated by two solid lines, (g, h and i as well as g' and i'): vapor flow in the heating zone into the cooling zone and reverse flow of the condensate to the heating zone. This simple model is changed because of friction between the vapor and the liquid, which leads to an entrainment of the surface layer of the liquid in the direction of the vapor flow[3].

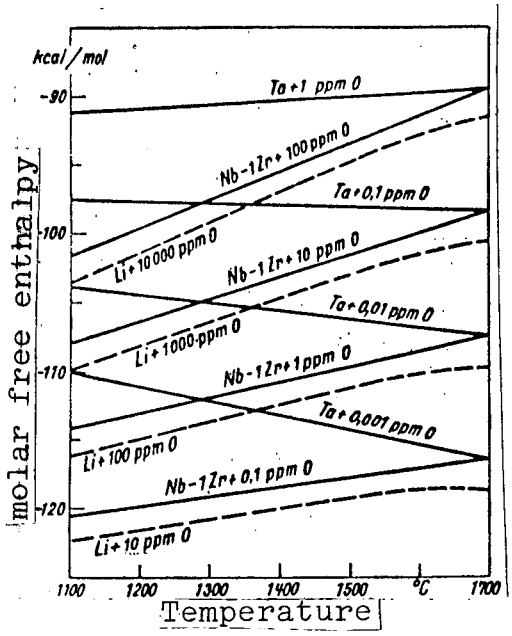

Figure 6. Changes of the molar free enthalpy for a solution of 1/2 mole O_2 (1 atm pressure, same temperature as the metal) in Li, Nb-1 Zr and Ta having various oxygen contents (calculated according to the Henry law [2]).

The first step of the corrosion process consists of the transfer of oxygen from the wall material of the cooling zone into the liquid Li. This transfer occurs as long as the partial molar free enthalpy of the oxygen in the wall material is larger than in the Li. Both free enthalpies depend on the oxygen concentration in the corresponding materials, as shown in Figure 6. A first estimation of the mass concentration of O in the Li of the cooling zone shows that it is on the order of a few 100 ppm [2]. Thus, it follows from Figure 6 that the Li can at the beginning take out almost all of the available oxygen at a mass concentration of approximately 100 ppm from the Nb-1 Zr and the Ta.

The second step of the corrosion process consists of transporting the dissolved oxygen in the heating zone. This transport is preferably carried out in the liquid layer near the wall

(circuits g and g' in Figure 5). The reason for this is that there is no turbulence in the liquid because of the low Reynolds number and also there is no important balancing of the concentration differences through the channel cross-section because of diffusion, because the available time is too small. The two liquid partial flows g and g' reach the boundary surface between the liquid and the vapor in the vicinity of the point A in Figure 5. Since the Li is much more volatile than the oxygen in the Li, the vaporization brings about a very great increase in the oxygen concentration in the liquid Li. Figure 7 shows the oxygen concentration in the /40
wall material of the heat pipes shown in Figure 3 after the experiment. The intensive deoxidization of the cooling zone can be observed, as well as the increase in the oxygen concentration up to 2000 ppm in the heating zone. The reason for the double maximum is probably the fact that the surface layer of the liquid is pulled along in the direction of the vapor flow. This transport leads to an accumulation of oxygen at the two ends B of the heating zone, as shown in Figure 5 by means of dashed lines.

The third step of the corrosion process consists of corrosion at the wall in the heating zone. With an ion analyzer we were able to show[4] that the wall penetration in Ta heat pipes where Li is used as the heat carrier is related with a ternary liquid Li-Ta-O phase. The details about the solution process of Nb or Ta in alkali metals in the presence of oxygen are not well known. The scanty experimental solubility data have a large amount of scatter, so that it was only possible to find laws for this process which had a great deal of uncertainty. The solubilities in K are probably the best known ones at the present time. Figure 8 shows measurement results of the dependence of the solubility of Nb in K as a function of the oxygen concentration in K. The sudden steep increase of the solubility when a certain oxygen concentration is exceeded is remarkable. In the distilled

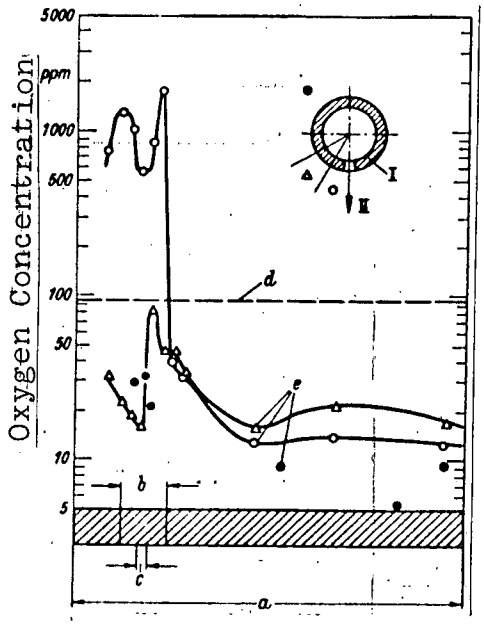

Figure 7. Mass concentration of oxygen in the wall of the Ta heat pipe shown in Figure 3 with Li as the heat carrier.

I cross-section through the heat pipe with gravity direction II and sectors from which the samples were taken. a-heat pipe with heating zone, b-(high frequency coil) and wall perforation; c, d-initial value of the oxygen concentration, e-measured values for the various (uncorroded) samples.

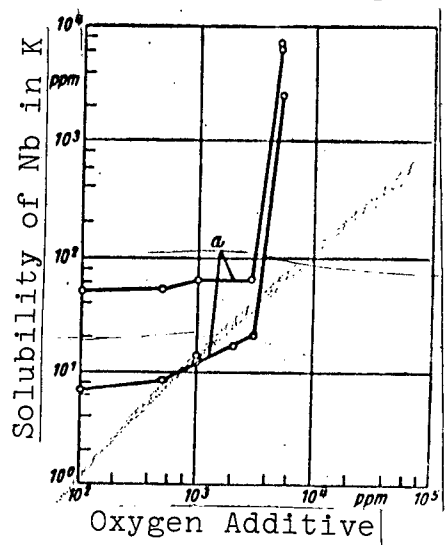

Figure 8. Solubility of Nb in K as a function of oxygen content (mass concentration) of K according to [5].
a-limits of the scattering region for the measured values taken at 1095°C.

K residue, we were able to chemically identify K_3NbO_4 (in the case of Ta we found K_3TaO_4)[6]. However, the form of the dissolved Nb in the K containing oxygen is not known (see, for example, reference 7).

For Li, the dependence of the solubility of Nb and Ta on the oxygen concentration at high temperatures is not known. It has been found that in heat pipes with Li as heat carrier, the Nb or Ta does not go into solution in the cooling zone but preferably goes into solution in the heating zone (i.e., at the place where there are high oxygen concentrations in the Li). This fact could be an indication that the solubility does not depend linearly on the oxygen concentration, similar to the situation in Figure 8. However, it must be remembered that the solubilities refer to equilibrium states. In general, these do not occur in the heat pipe. This means that corrosion attack does not only depend on solubility, but also on the kinetics of the solution process.

The large local accumulation of impurities is especially troublesome during heat zone corrosion. This means that even very small amounts of impurities can trigger the corrosion. This accumulation effect is favored by the fact that in the heat pipe, the ratio of the masses of liquid metal and wall material is especially small. Therefore, mixing effects in the liquid phase are very rare. This is because the liquid is mostly laminar and, as a rule, it vaporizes because of surface boiling. For this reason it is questionable whether it is possible to establish the suitability of any material combination using "refluxing capsule tests". (Capsules of this type are about half filled with liquid. The vaporization often is in the form of the boiling of bubbles). /41

Summarizing, we may say that both corrosion processes incorporate material transport from the cooling zone into the heating

TABLE 1. LIFETIME RESULTS OF Li HEAT PIPES WITH LIQUID GETTER ADDITIVES.

Wall material	Filling	Experimental Conditions		
		Temperature °C	average heat performance density W/cm^2	Duration h
Nb–1 Zr	Li–13 Ca	1500	115	1000*)
Nb–1 Zr	Li–40 Pr	1500	115	52**)
Ta	Li–13 Ca	1600	170	208**)
Ta	Li–40 Pr	1600	170	94**)
Ta	Li–0,5 Y	1600	170	21**)
Ta	Li–3 Y	1600	170	607**)
Ta	Li–15 Y	1600	145	146**)
Ta	Li–0,5 Sc	1600	145	357**)
Ta	Li–15 Sc	1600	145	16**)

*No failure but intensive grain growth, small Zr-, Li-, and Ca loss as well as swelling.

**Wall penetration in the heating zone.

zone. The reason for this is the fact that the volatility of the corresponding material in the heat carrier is too small. This leads to such a small concentration of the material in the vapor and of the condensate in the cooling zone, that the molar free enthalpy of the material in the condensate takes on smaller values than in the wall of the cooling zone. In one case, the transported material consists of the wall material itself. In the other case, we are only dealing with impurities in the wall material. In the first case, the heat pipe fails because of closing of the capillaries in the heating zone (coupled with the formation of leaks in the cooling zone). In the second case the impurities, which are concentrated in a small region of the heating zone, bring about a dissolution of the capillary structure by means of a reaction with the wall material. Finally there is wall penetration. A very small degree of heating zone corrosion can lead to a perforation of the thin, fine and porous net covering

and therefore to a reduction of the heat transport capacity. This is especially true for capillary structures for very high heat flux densities (for example, a ring gap between the pipe wall and a net covering, or grooves with net covering).

3. ATTEMPTS TO SOLVE THE CORROSION PROBLEMS

3.1 Prevention of Mass Transport

The decisive quantity for mass transport is the mass fraction $\bar{x}$ of the wall material in the heat carrier. An estimation of the highest permissible value can be obtained from equation (1). The heating power density $\dot{q}$ and the operational time t are specified quantities, for which we can assume the values 50 W/cm^2 and 10^4 hours, for example. The average layer density ϱ will be on the order of the wall material thickness, which is about 0.1 $mole/cm^3$ for refractory metals. The heat of vaporization L takes on values of about 180 kWs/mole for heat carriers which can be used in high temperature heat pipes. If it is assumed that a layer thickness of $s=0.1$ mm can be tolerated, then according to equation (1), the average molar concentration of the dissolved wall material in the heat carrier cannot be greater than 0.1 ppm. Since the concentration of the wall material in the heat carrier is limited by solubility, the mass transport can be maintained at sufficiently low levels if material combinations having a solubility below 0.1 ppm are used.

A difficulty occurs because usually no experimental solubility data are available for the material combinations under consideration. The solubilities can be calculated from the solubility parameter theory. However, it is not known whether this theory is applicable for the small solubilities [8]. Nevertheless, the theoretical solubilities are usually so small that the mass transport should

have no effect at all. Experiment seems to indicate that this is not true. For example, in the Ta-Tl system shown in Figure 1, the solubility parameter theory gives a solubility value of 10^{-4} ppm (molar concentration) at 1600° C. This value is too small by several orders of magnitude if it is to explain the mass transport shown in Figure 1.

Therefore, we may ask whether the observed mass transport is indeed the result of a "true" solubility of the system or whether it is due to a "apparent" solubility based on the impurities. It is possible that an impurity which increases the solubility and has sufficient volatility itself, could circulate continuously with the heat carrier and would then bring about the mass transport. In this case it should be possible to reduce the mass transport by cleaning the system.

3.2 Prevention of the Hot Zone Corrosion

Two attempts have been made to remove the hot zone corrosion: 1. removal of the impurities from the heat pipe, 2. getting of the impurities in the heat pipe. The corrosion process itself can be used for the first method. Since disturbing impurities accumulate in the heating zone, a clean heat pipe can be obtained after a certain operational time of the heat pipe by separating the heating zone [9]. This method was tested on a Nb-1 Zr heat pipe with Li, which was first operated for 95 hours at 1500° C until a leak appeared in the heating zone[2]. The defective heat zone was cut away with an electron beam. The remaining heat pipe then tolerated a one thousand hour experiment at 1500° C without failure. There was only a slight corrosion attack in the heating zone, as

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[2] This large lifetime, compared to the heat pipe shown in Figure 2, is probably based on the fact that the heating zone was lined with a Zr lining.

examination after the experiment showed. This is probably caused by the residual oxygen or by the oxygen uptake after the deoxidization.

If it is known which impurities trigger the heating zone, it becomes possible to make the heat pipe out of materials which contain the impurity in question in very small concentrations. We experimented with a Ta-Li heat pipe. Instead of the normal Ta, it was made of SGS-Ta, which contains less oxygen (oxygen mass concentration about 10 ppm), and was operated for 1000 hours at a heat power density of 170 W/cm^2 at 1600° C. There was no heating zone corrosion at all and only a very small mass transport [9]. The oxygen concentration of the SGS-Ta apparently is not low enough to avoid the heating zone corrosion in all cases. A SGS-Ta heat pipe with Li, the length and power level of which was twice as large as the corrosion-free heating pipe just mentioned, failed after 220 hours at 1600° C because of oxygen corrosion [4].

Table 1 contains some examples for the second method, the getting of the impurities in the heat pipes. These are Li heat pipes with Nb-1 Zr and Ta as the wall material. Here an attempt was made to avoid oxygen corrosion by additives having a high free formation enthalpy of the oxide (Ca, Pr. Y, Sc). Table 1 shows a comparison with the heat pipes of Figures 2 and 3. It can be seen that the lifetime was usually increased by one order of magnitude by an appropriately measured getter additive. However, only the Nb-1 Zr heat pipe with Ca additive and operated with Li withstood an experiment lasting more than 1000 hours. This heat pipe showed the beginnings of wall dissolution at the point of the heating zone. Oxygen concentrations up to 1780 ppm were measured in the vicinity of this point. /42

4. RESULTS OF LIFETIME EXPERIMENTS

Table 2 gives a summary of the best results obtained up to the present in lifetime experiments using high temperature heat pipes. At temperatures to about 1500° C, we obtained a lifetime of about 10,000 hours [10] with a TZM-Li heat pipe[3]. The same system failed after 4600 hours at a somewhat higher temperature because of heating zone corrosion. The reason for this could not be established with certainty [11].

At 1600° C, experiments using the 15 different combinations of the three wall materials (Nb-1 Zr, Ta, W) and the five heat carriers (Bi, Pb, Tl, Li, Ba) showed that the smallest corrosion is obtained with the W-Li heat pipe [8]. Here we found only a practically negligible mass transport, which led to the development of certain crystals in the heating zone. These can be seen in Figure 9 along the side walls of the longitudinal grooves which represent the capillary structure. We were able to estimate that the average molar concentration of the W in the Li arriving in the heating zone is on the order of about 10^{-4} ppm. The second best system in this experiment was found to be the W-Pb system, which, however, no longer has a negligibly small mass transport (see Figure 4). An experiment with the W-Li system at higher temperatures (planned up to 1800° C) is in process in the United States [11].

In order to avoid the problems associated with the brittleness of W, a long time experiment using a W-26 Re heat pipe and Li as a heat carrier has been started at Ispra for the 1600° temperature. The heat pipe properties have not changed after 6000 hours of operation.

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[3] TZM refers to a Mo alloy with a 0.8 % Zr, 0.5% Ti and 0.03% C content.

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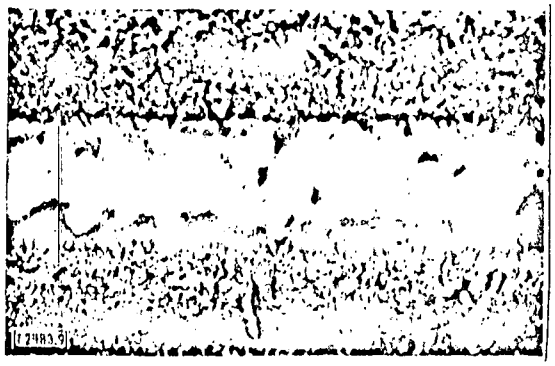

Figure 9. W-Li heat pipe after 1000 hours at 1600° C with an average heating performance density of 70 W/cm^2.

View of a capillary groove 0.4 mm wide in a heat pipe cut longitudinally, Li removed.

TABLE 2. SELECTED RESULTS OF LONG-TIME EXPERIMENTS WITH HIGH TEMPERATURE HEAT PIPES.

Wall Material	Heat Carrier	Temperature °C	average heat performance density W/cm^2	experimental duration h	Source	Remarks
TZM	Li	1475 1500	20	10 526	[10]	Leaking of a welded seam
TZM	Li	1560	190	4 600	[11]	Wall perforation in the heating zone
W	Li	1600	70	1 000	[8]	no failure
W	Pb	1600	80	1 000	[8]	no failure
W–26 Re	Li	1600	100	>6 000	Ispra	experiment in process
Ta–10 W	Ca	1700	–	365	[12; 13]	refluxing capsule
W	Ag	1900	–	1 000	[14]	no failure
Re	Ag	2000	–	(1 000)	[15]	small leak in the heating zone
W–26 Re	Ag	2000	154	1 000	Ispra	no failure

We would like to mention the reflux experiments for the material combinations TZM-In, Nb-1 Zr using Pb, Ca and Ba as well as Ta-10 W with In, Ca, Pb, Tl and Ba which are being performed in the United States [12, 13]. Some of these experiments extend to 1800° C. In section 2.3 we indicated the limited information that can be obtained from such reflux capsule experiments because of the behavior of the materials under heat pipe conditions. Nevertheless, it is remarkable that these experiments resulted in a very small corrosion for Ta-10 W with Ca (10 µm intergranular penetration after 1000 hours at 1700° C). Experiments on the behavior of this system as a heat pipe have not yet been published. At even higher temperatures, we should mention an experiment with a W-Ag heat pipe, which after 1000 hours of operation at 1900° C still has a negligibly small mass transport [14].

The highest experimental temperatures are 2000° C. An experiment at Los Alamos with Re-Ag failed after 365 hours because of a small leak in the heating zone. This leak seems to have been caused by volatile foreign matter included in the Re. Because of the negligibly small mass transport it was concluded that the Re-Ag system without these foreign inclusions would lead to substantially higher lifetimes [15]. An experiment was carried out at Ispra at 2000° C using a W-26 Re heat pipe with Ag. After 1000 hours there was only a moderate degree of mass transport. In this case the appearance of the corrosion was not the usual one. The wall material had dissolved out of the center of the condensation zone and was deposited in the heating zone as well as at the end of the condensation zone. This corrosion mechanism has not been interpreted as yet.

5. CONCLUDING REMARKS

In the past six years it has become possible to increase the lifetime of high temperature heat pipes from a few hours to on the order of ten thousand hours. Also the mechanism of the corrosion processes in heat pipes have been partially explained. It is particularly important that several Li systems have proven to be promising because Li has favorable heating properties. Also, very large axial heat flux densities are possible with relatively low vapor pressures (for example at 1700° C, the maximum is /43
500 kW/cm^2 [16]. However, the fact that the investigations made up to the present are only individual experiments means experiments on a broader scale must be carried out in order to be certain that no surprises will be encountered.

REFERENCES

1. Busse, C. A., R. Caron, F. Geiger and M. Pötzschke. Performance studies on heat pipes. Internat. Conf. on Thermionic Electrical Power Generation, London 1965, London: Inst. of Electr. Engrs. 1965. /43

2. Busse, C. A. Corrosion in High Temperature Lithium Heat Pipes with Niobium-1 Zirconium or Tantalum wall material, Corrosion Science, Vol. 10, No. 2, 1970, pp. 65-84.

3. Hufschmidt, W., E. Burck, G. Di Cola and H. Hoffman. The influence of the shirring effect of the vapor flow on the laminar liquid flow in capillaries of heat pipes. Wärme- and Stoffübertragung, Vol. 2, No. 4, 1969, pp. 222-39.

4. Quataert, D., and C. A. Busse. Study of the corrosion mechanism in high temperature lithium heat pipes by the ion analyzer. To be published in J. Nucl. Mat.

5. Cleary, R. E., S. S. Blecherman and J. E. Corliss. Solubility of refractory metals in lithium and potassium. Bericht TIM-850. Middletown: Pratt and Whitney Aircraft, 1965.

6. Stecura, S. Apparent solubilities of commercially pure and oxygen-doped tantalum and niobium in liquid potassium. Nat. Aeron. Space Adm. (NASA) TN D-5875, Washington, 1970.

7. Klueh, R. L. Interactions in alkali metal solutions containing oxygen. Teil 1: The niobium-oxygen-potassium system. Oak Ridge Nat. Lab. (ORNL) TM-2476, Oak Ridge, 1969.

8. Busse, C. A., F. Geiger, D. Quataert and M. Potzschke. Heatpipe life-tests at 1600° C and 1000° C. In: IEEE Conf. Record of the 1966 Thermionic Conversion Specialist Conference, Houston. New York: Inst. of Electrical and Electronics Engrs., 1966, pp. 149-58.

9. Busse, C. A., F. Geiger, H. Strub, M. Pötzschke and G. Kraft. High temperature lithium heat pipes. In: Proc. 2nd Internat. Conf. Thermionic Electrical Power Generation, Stresa. Bericht EUR4210 f. e. Ispra: Euratom, 1968, pp. 495-506.

10. Rouklove, P. Discussion remark. In: Proc. 2nd Internat. Conf. Thermionic Electrical Power Generation, Stresa. Bericht EUR4210 f. e. Ispra: Euratom, 1968, p. 494.

11. Shefsick, P. K. and D. M. Ernst. Heat pipe development for thermionic applications. In: Proc. 4th Inter-society Energy Conversion Engineering Conference, Washington, D. C. New York: Amer. Inst. of Chem. Engrs., 1969, pp. 879-87.

12. Johnson, G. D. Corrosion studies of liquid metal heat pipe systems at 1000° C to 1800° C. In: Draley, J. E., and J. R. Weeks - Corrosion by liquid metals. New York: Plenum Press 1970, pp. 321-37.

13. Johnson, G. D. Compatibility of various high-temperature heat pipe alloys with working fluids. In: IEEE Conf. Record of 1968 Thermionic Conversion Specialist Conf., Framingham. New York: Inst. of Electrical and Electronics Engrs., 1968, pp. 258-65.

14. Grover, G. M., J. E. Kemme and E. S. Keddy. Advances in heat pipe technology. In: Proc. 2nd Internat. Conf. Thermionic Electrical Power Generation. Stresa. Report EUR4210 f. e. Ispra: Euratom, 1968, pp. 477-90.

15. Quarterly status report on the space electric R and D program for the period ending January 31, 1969. Los Alamos Scientific Laboratory. Part 1, LA-4109-MS, 1969.

16. Busse, C. A. Theory of the sonic heat transfer limit of heat pipes. To be published in Internat. J. Heat Mass Transfer.

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